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Replaceable Blade Turbine and Stationary Specimen Corrosion Testing Facility

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REPLACEABLE BLADE TURBINE AND STATIONARY SPECIMEN CORROSION TESTING FACILITY

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SUMMARY

A facility was constructed to provide relatively low cost testing of hot section turbine blade and vane materials under hot corrosion conditions more akin to service environments. The facility consists of a small combustor whose pressurized gas flow can be directed to either a test section consisting of three small cascaded specimens or to a partial admittance single-stage axial flow turbine. The turbine rotor contains 28 replaceable turbine blades. The combustion gases resulting from the burning of Jet A-1 fuel can be seeded with measured amounts of alkali salts. This facility is described here along with preliminary corrosion test results obtained during the final checkout of the facility.

E-2371

INTRODUCTION

A facility was constructed at NASA Lewis Research Center (LeRC) to provide relatively low cost testing of hot section turbine blade and vane materials under hot corrosion conditions akin to actual service environments. Corrosion testing on a test stand gas turbine engine is extremely expensive and the data collected from such a facility may not be applicable to other gas turbine engines. In the other extreme, inexpensive laboratory testing of various aspects of the corrosion processes can be conducted with sufficient control to provide modeling information but there remains the task of verifying the validity and applicability of the model to actual engine conditions. Between these extremes are numerous burner rigs, apparatus varying in complexity from low to high gas velocity, operating at atmospheric to elevated pressures, and employing stationary or rotating specimens with various geometries such as cylinders, wedges, airfoils, etc. The utility of such rigs has been mainly in the evaluation of the relative oxidation or hot corrosion resistance of newly developed alloys and coatings. Recent work, however, has suggested the possibility of conducting corrosion mechanisms studies in a well instrumented and properly characterized high velocity burner rig (ref. 1).

The facility described here was constructed to provide direct information on the effect of aerodynamic forces on the oxidation and hot corrosion of turbine blades fabricated from various superalloy materials with or without coatings. A goal was to provide test results that could be compared to stationary specimen data and to do this at minimum cost.

The facility consists of a small combustor whose pressurized gas flow can be directed to either a test section consisting of three small cascaded specimens or to a partial admittance single-stage axial flow turbine. The turbine rotor has 28 replaceable turbine blades. This facility is described here along with preliminary corrosion test results obtained during the final checkout of the facility.

N85-18126#

Overview of the Facility

The so called RBT (replaceable blade turbine) facility consists of three main sections, a common combustor, a stationary specimen test leg and a single stage partial admittance axial flow turbine leg (see fig. 1). Combustion gases at temperatures up to 1000 °C (1830 °F) are conducted through a 5.1 cm diameter (2 in) pipe, fabricated from the alloy, RA 330,[1] to either the stationary specimen leg or the turbine leg. The gas carrying inner pipe is contained within but insulated from a 12.7 cm (5 in) diameter gas tight outer pipe. The maximum flows are; 90.7 gm/sec (0.2 lb/sec) for the combustion air and 10.6 l/hr (2.8 gal/hr) for the Jet A-1 fuel. The maximum fuel to air ratio is 0.026. The rig can be pressurized up to 4×10^5 N/m^2 gauge (4 atm, gauge).

The combustor consists of a housing and a 5.1 cm (2 in) diameter liner and is similar to those used in the Mach 0.3 burner rigs at NASA Lewis (ref. 2). The stationary specimen test leg contains an inner oval pipe insulated from an outer rectangular housing with three ports for access to the specimens. The specimens are located 30.48 cm (12 in) apart in this test section so as to allow flow recovery between specimens. The 12.7 cm tip-diameter turbine is an axial flow single-stage unit. The rotor accommodates 28 replaceable blades. The inlet stator to the turbine has four guide passages to provide approximately 16 percent partial admittance.

The rig is designed to operate unattended for as long as 100 hr at a time. To do this the facility is equipped with a data acquisition and display system called Escort (ref. 3), and an automatic shutdown system that shuts down the rig in a prescribed sequence when an out-of-limit condition is detected. For ease of troubleshooting, a series of lights indicate which sensor initiated the shutdown. A programmable controller replaces much of the hard wiring, such as relays and timers, so as to provide, among other tasks, the necessary permissives for safe operation of the rig. For example, ignition is not possible without proper combustion air flow and other conditions first being satisfied.

Combustor and Stationary Specimen Leg

Figure 2 is a simplified, schematic flow diagram showing the combustor, the stationary specimen leg, and the salt solution injection system. Appendix A identifies the symbols employed in all the flow schematics in this report. Primary control of the rig is directed at controlling sample temperature by adjusting the fuel to air ratio. This requires precise control of both the fuel and air flows. Air flow is set to maintain a specified flow velocity while fuel flow is set to produce a specified sample temperature. Combustion air mass flow is determined from the pressure drop across a calibrated venturi at a measured air temperature and pressure,

$$\dot{m} = K\sqrt{\frac{P\Delta P}{T}} \tag{1}$$

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[1]Compositions of all alloys mentioned in this paper are presented in table I.

where $\dot{m}$ is the combustion air mass flow, K is a constant for the purpose of control, P is the air pressure, T is air temperature, and ΔP is the pressure differential across the venturi. The electrical output of the sensors which measure P, ΔP, and T, are suitably combined (using a calibrated voltage multiplier-divider and a square root extractor) to produce a voltage output represented by equation (1). The combustion air flow is set and controlled by a closed loop system whereby the processed signals of the three sensors provide a signal to a controller that operates an electric-to-pneumatic transducer. This transducer adjusts an air flow valve in response to deviations from the set point of the controller to maintain a constant predetermined flow. The constant K has a value determined by a combination of variables and constants related to flow conditions and hardware dimensions. However, K can be considered a constant for purposes of controlling air flow in the range of interest. The Escort data collection system and computer used the P, ΔP, and T signals and all other pertinent variables and constants from the calibration of the venturi to calculate a precise mass flow.

The fuel flow is also controlled by a closed loop system, where a thermocouple downstream of the burner provides a signal source to a controller that adjusts the fuel valve via an electric-pneumatic transducer to maintain the set point flow for the desired combustion gas temperature.

Two other closed loop controls are shown in figure 2, one maintains the pressure of the system constant at a selectable value up to 4 atm and the other provides the proper amount of water flow to quench the hot gases before they exit the system.

The flame can be doped with desired salts by an injector system. Diluted salt solution is pumped into a salt injector by a diaphram pump whose stroke length and frequency adjustments determine solution flow rate. The solution is atomized into small droplets in the injector. The atomizing air is kept at a 20 psi bias with respect to the pressure in the combustor.

Figure 3 is a photograph of the test section of the stationary specimen leg. The test section consists of an inner oval tube whose cross-sectional dimensions are given in figure 4. The inner tube is insulated from an outer rectangular tube measuring 0.91 m (3 ft) long by 10.2 cm (4 in) high and 15.2 cm (6 in) wide. The test section has three ports for access to the three specimens. The specimens are located 30.5 cm (12 in) apart to allow for combustion gas flow recovery between specimens. Two specimen geometries are used, small cylinders or pins and coupons, see figure 4 for dimensions. The size of the test specimens and the geometry of the inner oval tube were designed so as to minimize flow disturbance from the specimens and the wall of the tube. The specimens are held in position by lava holders. At 980 °C (1800 °F) and 4.13×10^5 N/m^2 (60 psia) the gas velocity in the test section is about 91 m/sec (300 ft/sec).

Replaceable Blade Turbine Leg

The replaceable blade turbine (RBT) leg consists of a partial admittance axial flow single-stage turbine with a 12.7 cm (5 in) tip diameter; a "paddle wheel" rotor airbrake with reversible flow (used both as a turbine starter and brake); controls for the pressure ratio across the turbine, for turbine speed and for quench water flow to cool the exhaust gases; and a lubrication system

for the turbine and airbrake bearings. The turbine is a modified version of the one designed by Haas and Kofskey (ref. 4), and the airbrake was essentially the one used with the integrally bladed turbine (IBT), as part of the pressurized fluidized bed coal facility at Nasa Lewis (ref. 5). Figure 5 is a photograph of the turbine and airbrake assemblies and figure 6 is a photograph of the disassembled turbine housing and rotor. Figure 7 is a simplified flow schematic of the turbine section.

The stator was fabricated out of a cobalt-base superalloy, Mar-M 509. Figure 8 is a photograph of a stator with its integral flange, showing the three vanes and four passages. The stator provided a 16 percent partial admittance of the hot gases with respect to the turbine rotor. The rotor contained 28 replaceable blades. This allows up to 28 different alloys to be tested simultaneously. Each blade was locked into its place in the rotor by a combination of a stopper tab at the root of the blade and a strip of metal fitting between the blade root and the rotor. This strip of metal was shaped to fit a notch at the bottom of the root of the blade and one end was bent to fit over the edge of the rotor after insertion into the wheel (fig. 9). Each rotor with its full compliment of blades was spin tested and balanced prior to final assembly of the turbine. The maximum designed rotation speed is 40 000 rpm. Table II lists the physical parameters of the rotor and table III lists some turbine run conditions.

As seen schematically in figure 7 the brake air flow is measured in the same manner as the combustion air flow, i.e., by the pressure drop across a calibrated venturi. Turbine speed is controlled by the opposing action of the airbrake on the aerodynamic forces of the combustion gases acting on the rotor of the turbine. A magnetic pickup on the shaft of the airbrake feeds a signal to the speed controller that adjusts a valve in the air flow line to the brake so as to maintain the set point value of the controller. The set point of the controller corresponds to the desired turbine speed as sensed by a magnetic pickup on the turbine shaft. Vibrations and out of roundness of the shafts of the turbine and the brake are sensed by accelerometers and proximity probes respectively. These sensors will initiate a shutdown when limits are exceeded. The pressure ratio across the turbine is maintained to the desired value by a controller that adjusts the back pressure valve in the exhaust line. Quenching of the exhaust gases is controlled in the same manner as in the stationary specimen leg. Lubricant oil flow to the bearings of the turbine and the brake was maintained by an oil pump. The oil was cooled by a water fed heat exchanger. A labyrinth seal on the turbine shaft and air directed to the labyrinth edges provided isolation of the lube oil from the combustion gases. The seal air also provided cooling for the hub of the rotor. The cooling was considered necessary to limit thermal expansion of the rotor so as to prevent the loss of the blades in the presence of centrifugal forces and to preserve the integrity of the rotor.

Final Checkout - Corrosion Testing

As a final checkout of the facility a 100 hr oxidation test was conducted in the stationary specimen leg and a 10-1/2 hr hot corrosion test was conducted in the RBT leg.

In the oxidation test IN100 superalloy specimens with the coupon geometry were used. The temperature of the combustion gases into the test section

during the duration of the test was 974±13 °C (1786±23 °F) and the pressure was 5.1×10^5 N/m^2 (74±4 psia). The pressure throughout the test section was uniform but the temperature of the three cascaded specimens and the gas temperature decreased in the flow direction with an average temperature drop of (8±3 °C) 15±5 °F between each specimen. The thermal gradient throughout the length of the test section is attributed to heat losses through the insulation to the outer housing, but particularly to losses around the specimen access ports. Aside from the thermal gradient within the test section, all systems in the combustor and stationary specimen leg functioned within design limits. The oxidized specimens showed no unusual attack so detailed analyses were not performed.

In the hot corrosion testing in the RBT leg, seven alloy compositions were tested with four blades of each alloy. As seen in the diagram in figure 10, one blade of each composition was placed in each quadrant of the rotor. The nominal compositions of the alloys are listed in table I.

During systems checks with hot flowing gases, prior to salt injection into the combustor, the maximum blade temperature registered by a two color optical pyrometer was 700 °C (1292 °F) with a combustion gas temperature to the stator of 980 °C (1800 °F) and a pressure of 4.1×10^5 N/m^2 (60 psia). The blade temperature was found to be influenced by the flow of seal air. This air not only separates the combustion gases from the bearing lube oil but also cools the rotor hub, which in turn extracts heat from the blades. The minimum seal air flow is dictated by the maximum temperature rating of the bearings, and under the conditions noted above, this resulted in a maximum blade temperature of 700 °C (1292 °F). It was found necessary to raise the inlet gas temperature to at least 1177 °C (2150 °F) in order to obtain the desired blade temperature of 900 °C (1650 °F) for hot corrosion testing. Unfortunately this meant operating the turbine beyond its designed inlet temperature. It was decided to conduct the hot corrosion test at the higher inlet temperature, but to reduce turbine speed to 10 000 rpm to ease the thermal load to the bearings.

The test conditions for the RBT hot corrosion test run are listed in table IV. The high salt concentration was intended to accelerate the corrosion attack. A concentration of 0.1 to 1 ppm Na with respect to the combustion air would be more realistic of service conditions. The test was conducted in two segments, a 6 hr run and a 4-1/2 hr run for a total time of 10-1/2 hr. Further testing was precluded because the turbine rotor seized. The cause of the sticking was attributed to lack of blade tip clearance due to the partial delamination of the shroud of the turbine housing. High inlet gas temperatures may have been responsible for the delamination.

After testing the blades were visually inspected in and out of the turbine housing (figs. 11 and 12, respectively). Surprisingly, the extent of corrosion was found to be dependent upon the relative location of the blades on the rotor. As seen in figure 12, for each composition the most severe corrosion occurred for those blades grouped in the third quadrant and the least for those grouped in the first quadrant. Supposedly, all the blades were exposed equally to the same environmental conditions, i.e., the blades were rotating whenever hot gases (with or without salt) were flowing through the turbine. An analysis of the water soluble deposits from the blades grouped in the third quadrant is presented in table V. The solutes are those typically found on hot corroded nickel base superalloys. Figure 13 presents the corrosion morphologies of two of the blades. These and all the blades possessed typical "high temperature"

type hot corrosion morphologies, i.e., porous oxide scales with included metal over an inner zone depleted of γ' (Ni_3Al,Ti) phase and containing sulfide particles. The corrosion pattern was also similar to that observed on turbine blades from service, i.e., corrosion occurred primarily on the tip and on the pressure surface.

CONCLUDING REMARKS

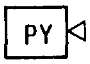
A facility has been constructed which can be used to study the corrosion of turbine blade-vane alloys at high temperatures and elevated pressures, either as stationary specimens or as blades on a single-stage axial flow turbine.

An analysis of the blades after a hot corrosion checkout test indicated that indeed the blades suffered typical "high temperature" type hot corrosion degradation with corrosion patterns similar to that observed on blades taken from gas turbines in service.

The minimum hub cooling needed to keep bearings cool prevented the blades from reaching sufficient temperature for corrosion at the designed inlet temperature. Raising the inlet temperature above the designed level to obtain a usable blade temperature apparently caused the turbine housing shroud to delaminate; thereby, seizing the blade tips. At the designed inlet temperature, the turbine performed at the desired speeds, pressures and pressure ratios and all subsystems (controls, automatic shutdowns, data acquisition, salt solution injection, etc.) performed according to design specifications.

APPENDIX A

Symbols used in the flow schematics

	pump
	filter
	rotameter
	turbine flow meter
	venturi
	hand valve
	solenoid valve
	pneu control valve
	press regulator
	bearings
	2 color optical pyrometer
$\boxed{\text{TC}}$	thermocouple
$\boxed{\text{PT}}$	press XDCR
$\boxed{\text{EP}}$	elec-pneu XDCR
$\boxed{\text{PDT}}$	press diff XDCR
$\boxed{\text{MP}}$	magnetic pickup
$\boxed{\text{FC}}$	frequency converter

L	loader
M	multiplier - divider
R	square root extractor
PIC	press indicate control
TIC	temperature indicate control
FIC	flow indicate control
SIC	speed indicate control

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4. Haas, Jeffrey E.; and Kofskey, Milton G.: Cold-Air Performance of a 12.766-Centimeter-Tip-Diameter Axial Flow Cooled Turbine. II - Effect of Air Ejection on Turbine Performance. NASA TP-1018, 1977.
5. Rollbuhler, R.J.; Benford, S.M.; and Zellars, G.R.: Improved PFB Operations: 400-Hour Turbine Test Results, NASA TM-81511, 1980.

TABLE I. - NOMINAL COMPOSITIONS OF THE ALLOYS REFERRED TO IN THIS REPORT, INCLUDING I.D. NUMBERS FOR THE BLADES OF THE TURBINE

I.D. number	Alloy	Ni	Cr	Co	Mo	W	Ta	Nb	Al	Ti	Fe	C	B	Zr	Others
	RA 330	35	19	----	---	---	---	---	----	---	Bal	0.5	-----	----	1.25 Si
	MAR-M 509	10	23.5	Bal	---	7	3.5	---	----	0.2	---	.6	-----	0.5	--------------
1	IN-100	Bal	10	15	3	---	---	---	5.5	4.7	---	.18	0.014	.06	1.0 V
2	IN-713LC	Bal	12	----	4.5	---	---	2	5.9	.6	---	.05	.01	.1	--------------
4	IN-792+Hf	Bal	12.4	9	1.9	3.8	3.9	---	3.1	4.5	---	.12	.02	.1	1.0 Hf
6	U-700	Bal	15	----	5.2	---	---	---	4.25	3.5	1.0	.15	.05	----	--------------
7	TAZ-8A	Bal	6	18.5	4	---	8	2.5	6	---	---	.12	.004	1	--------------
8	TRW-1800	Bal	13	----	---	9	---	1.5	6	.6	---	.09	.07	.07	--------------
9	TRW-NASA-V1A	Bal	6.1	7.5	2	5.8	9	0.5	5.4	1	---	.13	.02	.13	0.5 Re, 0.4 Hf

TABLE II. - TURBINE ROTOR PHYSICAL PARAMETERS

Parameters	Value
Actual cord	2.102 cm
Axial cord	2.062 cm
Leading edge radius	.081 cm
Trailing edge radius	.036 cm
Radius	
Hub	5.331 cm
Mean	5.857 cm
Tip	6.383 cm
Blade height	1.051 cm
Aspect ratio	.50
Number of blades	28
Radius ratio	.835

TABLE III. - TURBINE RUN CONDITIONS

Rotation speed			Pressure ratio	Power, hp
rpm	m/sec	(ft/sec[a])		
40 000	244	(800)	1.75	10.4
30 000	183	(600)	1.36	5.9
15 000	91	(300)	1.08	1.5

[a]At mean radius.

TABLE IV. - RBT HOT CORROSION TEST CONDITIONS

Parameter	Value
Mass air flow	139 Kg/hr (306 lb/hr)
Mass fuel flow	3.4 Kg/hr (7.4 lb/hr)
Fuel/air ratio	0.024
Inlet gas temperature	1177 °C (2150 °F)
Blade temperature	900±20 °C (1650±36 °F)
Turbine speed	10 000 rpm
Pressure ratio	1.08
Na concentration (as Na Cl) with respect to the combustion air	8 ppm
Test duration	10.5 hr

TABLE V. - WATER SOLUBLE DEPOSITS ON BLADES OF THE THIRD QUADRANT

Alloy	Na	SO_4	Cr	Mo	Al	Ni
			(mg)			
IN-100	10.8	24.75	0.050	0.370	N.D.	<0.005
IN-713LC	9.9	20.12	.094	.150	<0.005	.011
IN-792+Hf	14.3	31.25	.110	.135	.005	.009
U-700	12.6	25.38	.190	.070	.005	.013
TAZ-8A	18.0	19.67	.180	.920	.005	.018
TRW-1800	12.2	26.12	.180	-----	.005	.013
TRW-NASA-VIA	13.2	27.62	.180	.090	.005	<.005

Precision for Na, Cr, Mo, Al, Ni = ±2-5%, for SO_4 = ±10%.

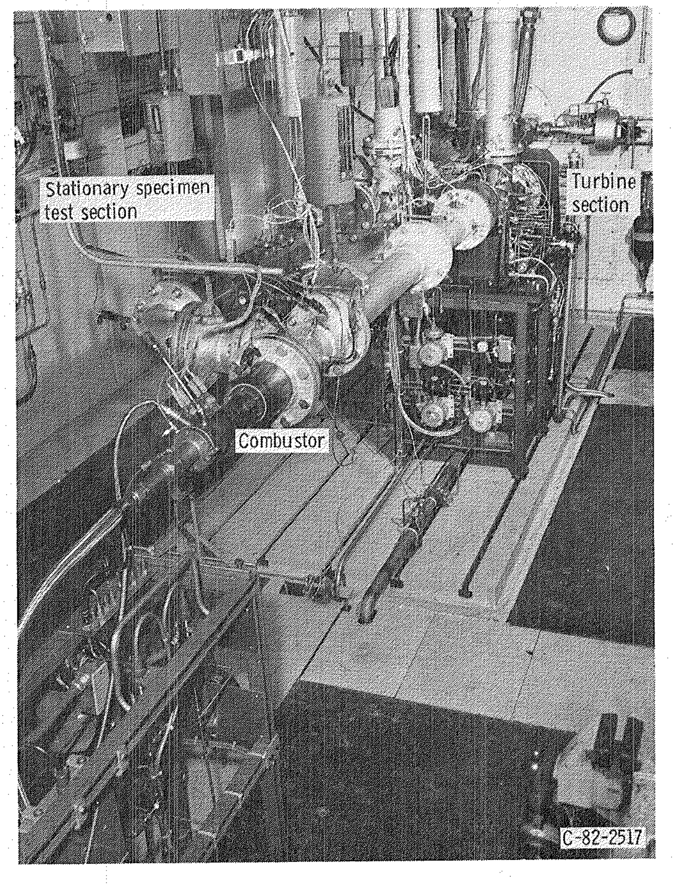


Figure 1. - Overall view of the RBT-Stationary Specimen Facility showing the three main components: combustor, RBT leg, and the stationary specimen leg.

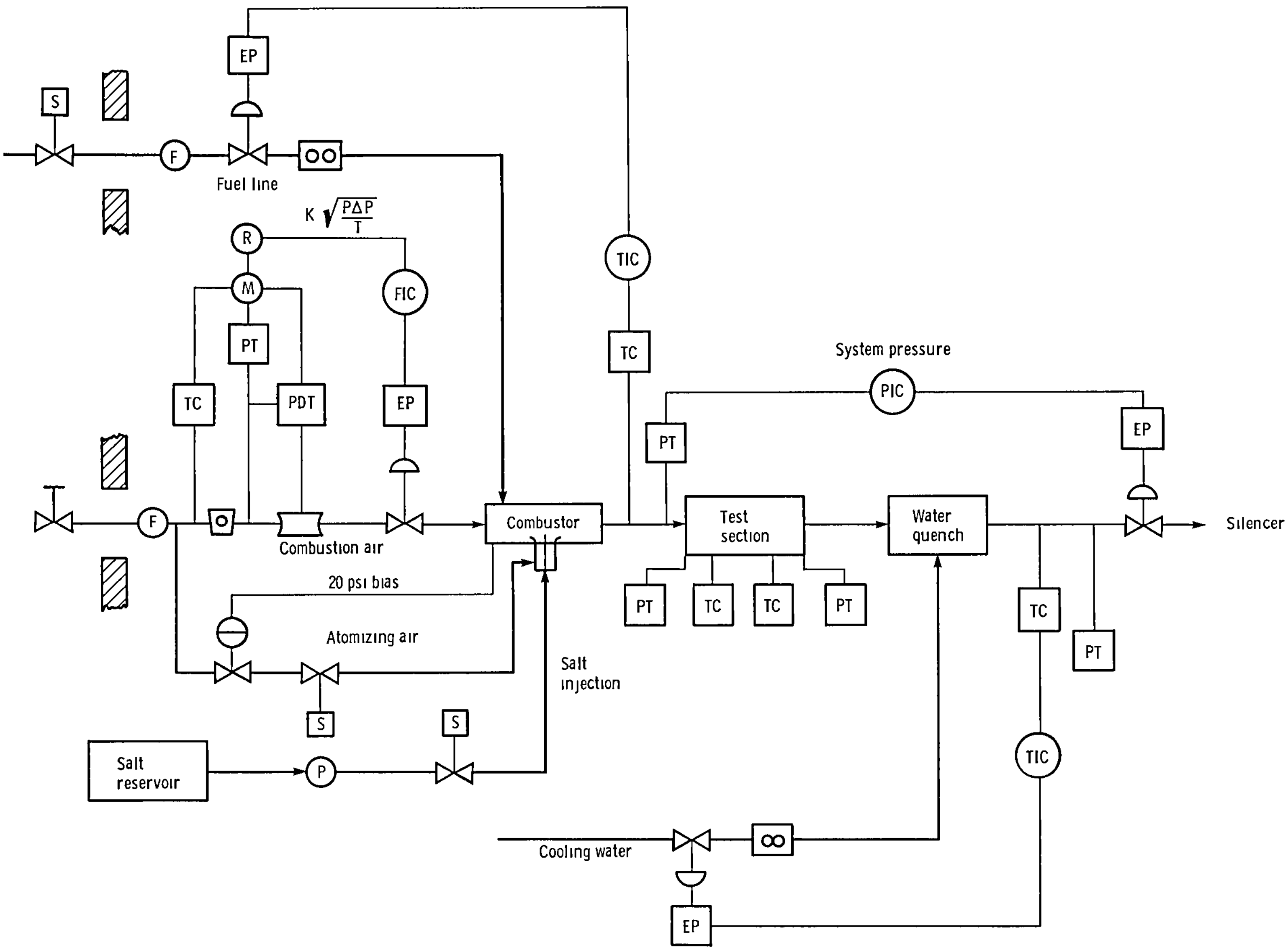


Figure 2 - Simplified flow schematic of the combustor, the stationary specimen leg and the salt solution injection system

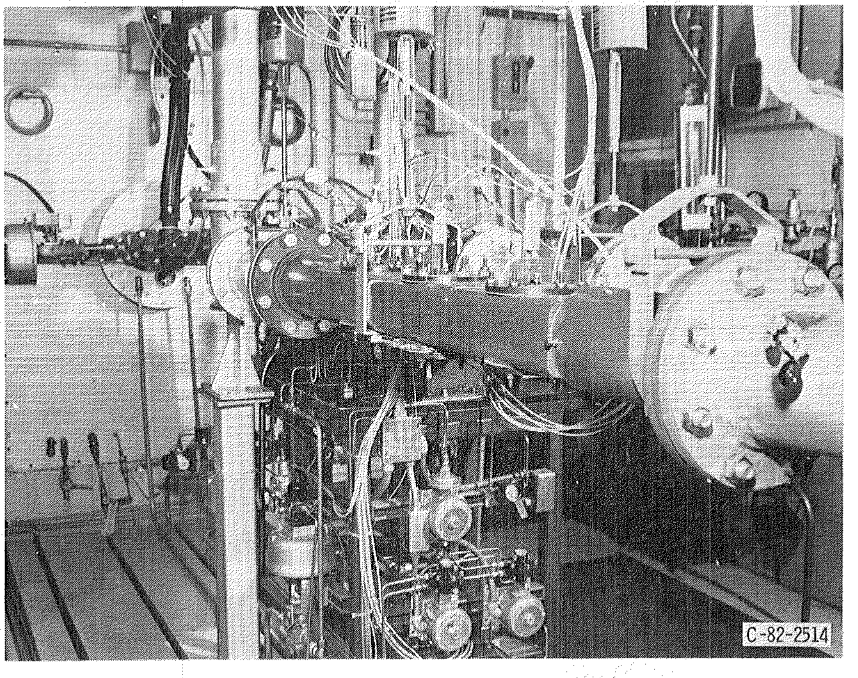
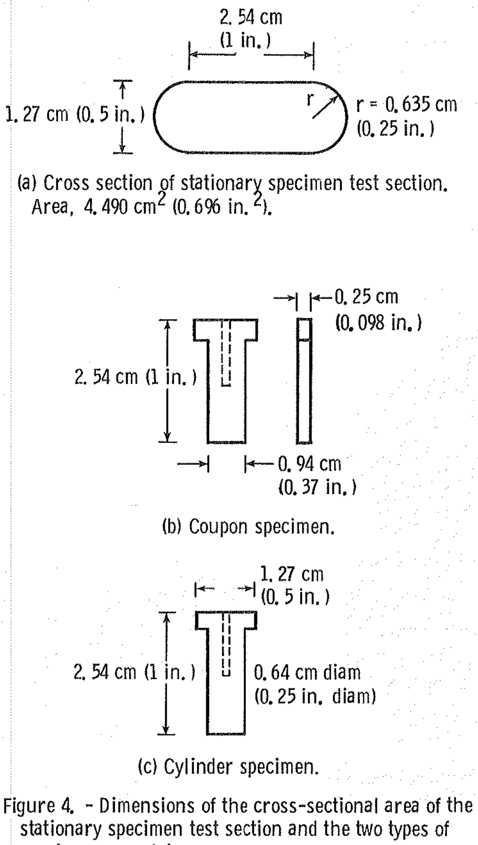


Figure 3. - Stationary specimen test section with a port for each of the three specimens.



(a) Cross section of stationary specimen test section. Area, 4.490 cm^2 (0.696 $in.^2$).

(b) Coupon specimen.

(c) Cylinder specimen.

Figure 4. - Dimensions of the cross-sectional area of the stationary specimen test section and the two types of specimen geometries.

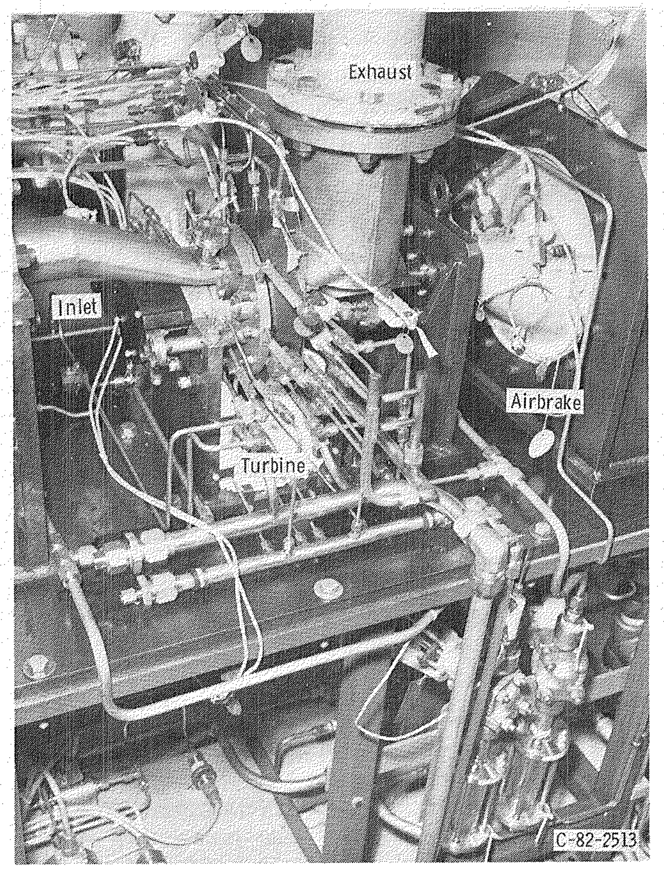


Figure 5. - The turbine and airbrake section of the RBT leg.

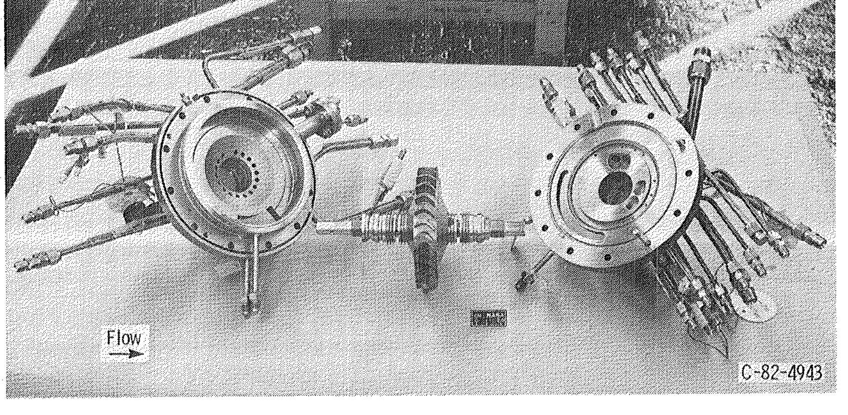


Figure 6. - Disassembled turbine with the two halves of the housing and the rotor with its replaceable blades. Not shown is the stator-flange assembly.

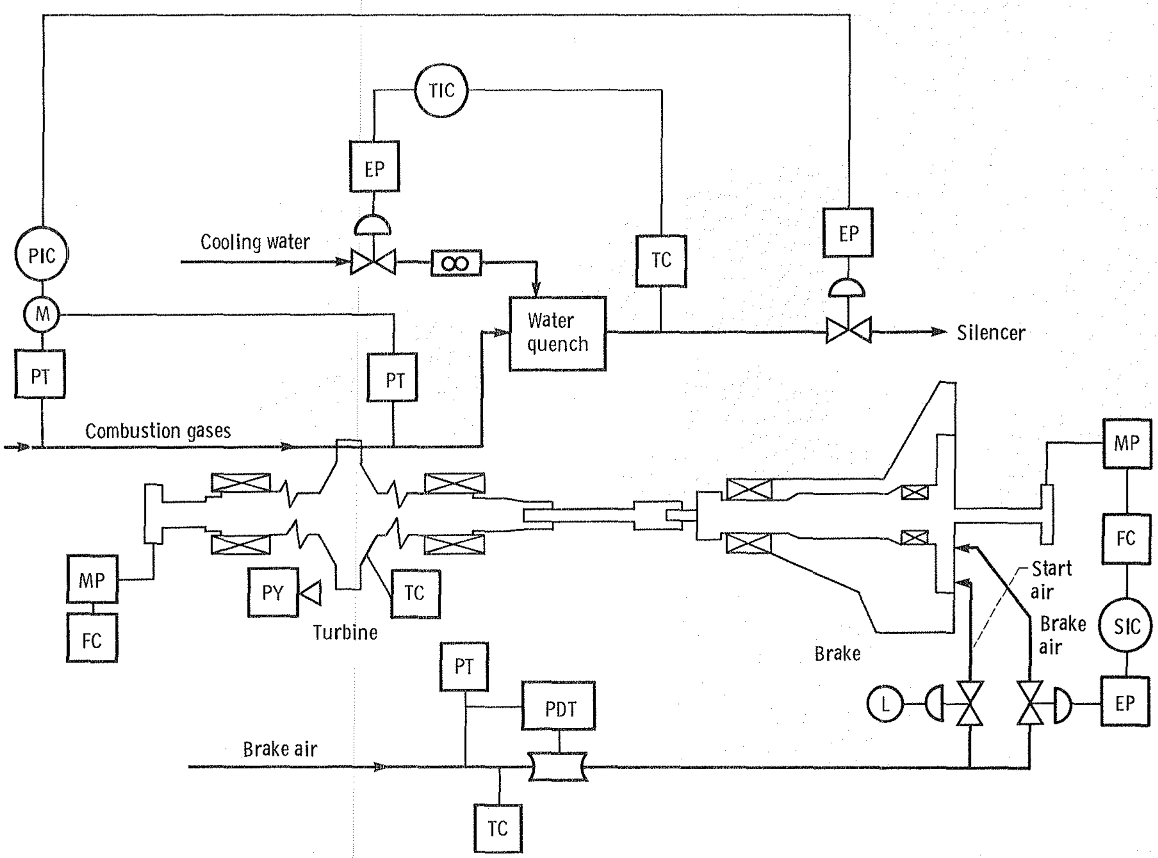


Figure 7. - Simplified flow schematic of the RBT leg.

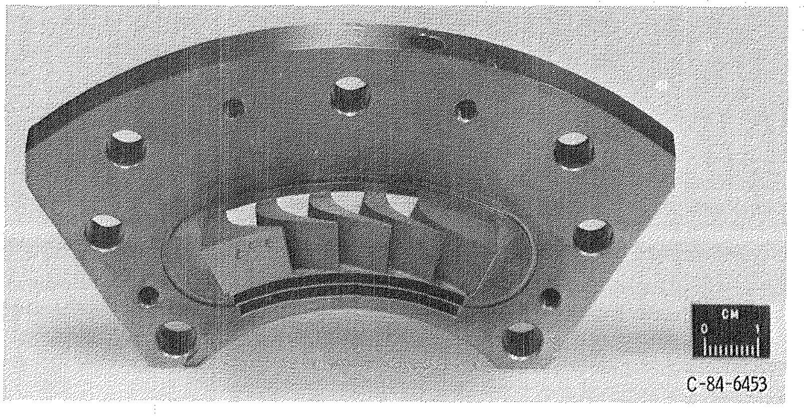


Figure 8. - Stator-flange assembly viewed from the trailing edges of the vanes.

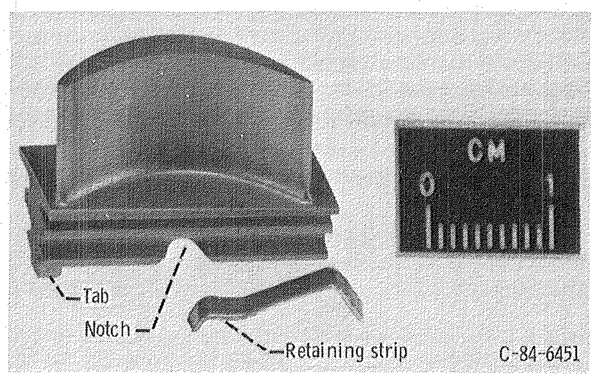
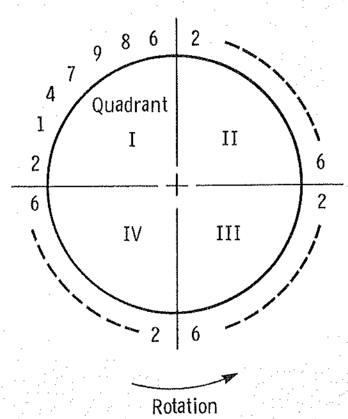


Figure 9. - Typical replaceable turbine blade indicating method of securing the blade to the rotor.



ALLOYS	BLADE IDENTIFICATION
IN-100	1
IN-703 LC	2
IN-792 + Hf	4
U-700	6
TAZ-8 A	7
TRW-1800	8
TRW-NASA-VI A	9

Figure 10. - Location of the 28 blades viewed from upstream on the turbine rotor with blade identification numbers.

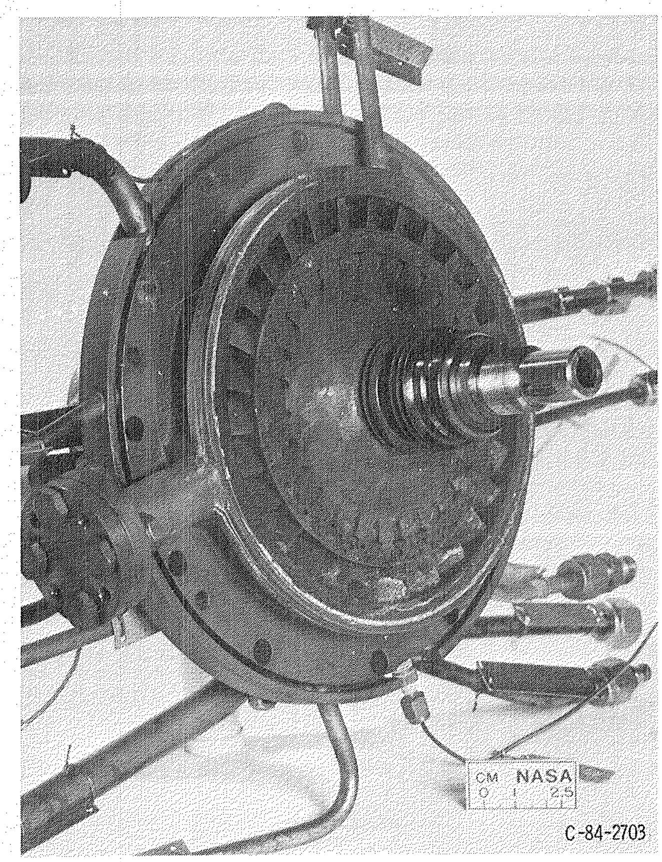


Figure 11. - Turbine rotor and corroded blades in the inlet half of the housing.

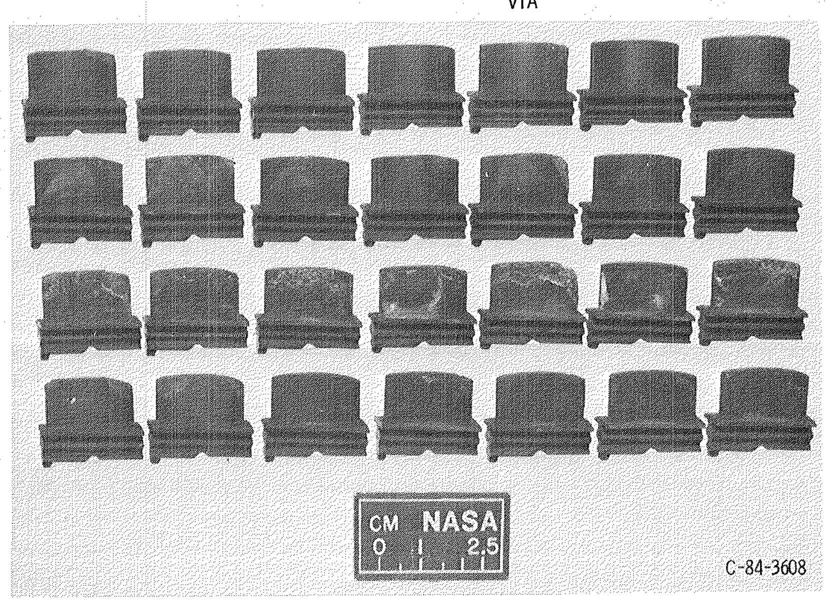
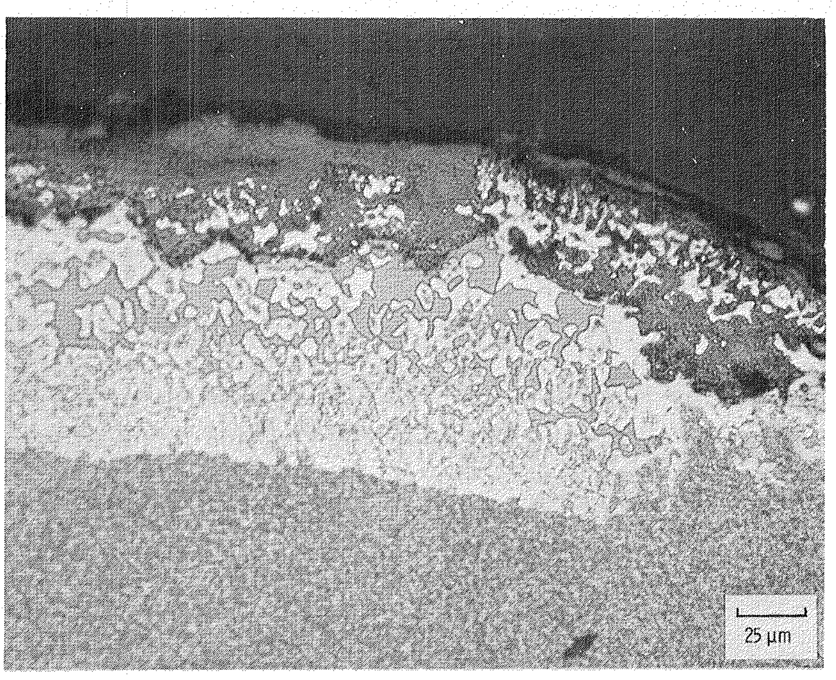
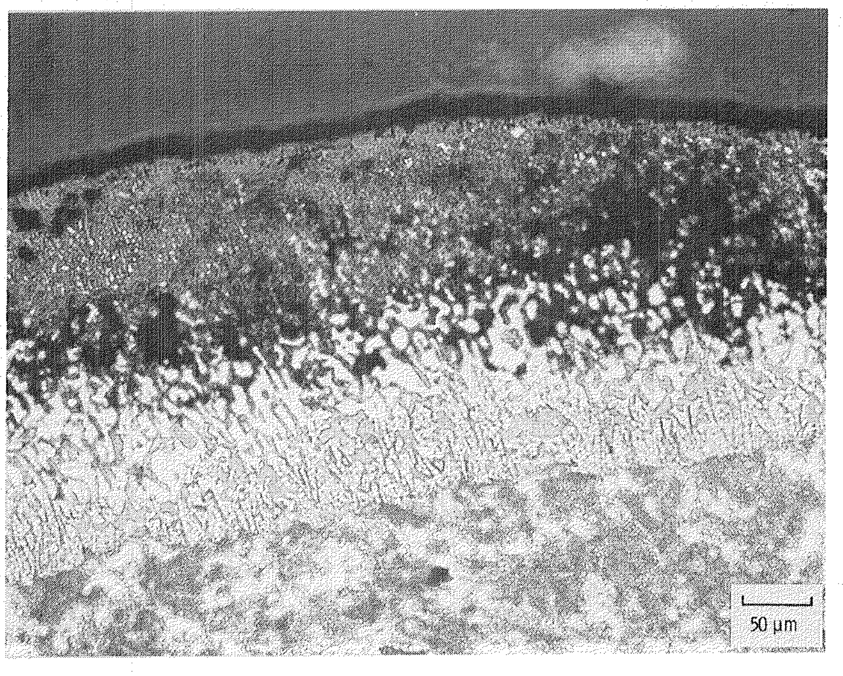


Figure 12. - Corroded blades after 10-1/2 hr at 900 ^{o}C, 4.1×10^{5} N/m^{2} (60 psia) pressure and 8 ppm Na in the combustion air.



(a) U-700 suction surface near leading edge.



(b) TAZ-8A pressure surface near the leading edge.

Figure 13. - Two of the seven alloys corroded in the RBT at 900°C for 10-1/2 hr and 8 ppm Na in the combustion air. All seven alloys displayed typical ''high temperature'' type hot corrosion degradation.

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15 Supplementary Notes

16 Abstract

A facility was constructed to provide relatively low cost testing of hot section turbine blade and vane materials under hot corrosion conditions more akin to service environments. The facility consists of a small combustor whose pressurized gas flow can be directed to either a test section consisting of three small cascaded specimens or to a partial admittance single-stage axial flow turbine. The turbine rotor contains 28 replaceable turbine blades. The combustion gases resulting from the burning of Jet A-1 fuel can be seeded with measured amounts of alkali salts. This facility is described here along with preliminary corrosion test results obtained during the final checkout of the facility.

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